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CASTING OF BERYLLIUM - STAINLESS STEEL AND BERYLLIUM - COLUMBIUM IMPACT TARGET COMPOSITES

by

C. J. Patenaude and W. H. Santschi

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-3729

THE BERYLLIUM CORPORATION
READING, PENNSYLVANIA

SUMMARY REPORT

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CASTING OF BERYLLIUM-STAINLESS STEEL

and

BERYLLIUM-COLUMBIUM IMPACT TARGET COMPOSITES

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SUMMARY

The objective of the work described herein was to make available to NASA tubular composites of cast beryllium-stainless steel and cast beryllium-columbium to serve as impact targets in tests of beryllium's resistance to simulated meteoroid collisions.

Four basic approaches were undertaken to produce these composites, all aimed at achieving a metallurgical bond at the Be-SS and Be-Cb interfaces: 1) direct casting of the beryllium around stainless steel and columbium tubing; 2) coextrusion of cast beryllium and stainless steel; 3) silver brazing of cast beryllium to stainless steel; and 4) solid state diffusion bonding of cast beryllium to stainless steel.

Direct casting was successful in producing beryllium-columbium targets but not beryllium-stainless steel owing to a low melting point eutectic in the system Be-Fe-Cr-Ni.

Coextrusion of beryllium with stainless steel was unsuccessful because of an unfavorable relationship between the thermal coefficients of expansion of the two materials in the desired configuration.

Both brazing and diffusion bonding with silver as the intermediary material were moderately successful.

Experimental techniques employed and the results of metallographic and radiographic evaluations are presented. A compilation of the targets produced is also included. Author

INTRODUCTION

Beryllium combines mechanical and physical properties which make it attractive for use as protective armor and fins for space radiators. For example, its high elastic modulus and low density combined with its high specific heat and thermal conductivity underscore this light metal's promise as a space radiator material.

While its favorable properties speak forcefully for beryllium as a first choice for minimum weight space radiators, additional information is needed in certain areas to warrant its use. For example, beryllium is generally considered brittle and has poor impact resistance. It has a propensity for texturing during hot working which causes anisotropic behavior. However, this shortcoming can often turn into an advantage if care is exercised in designing parts or assemblies. In addition, reported work on joining beryllium to metals such as those studied in this program is anything but abundant. Good metallurgical joints are, of course, of paramount importance to heat transfer.

The aim of this program was to develop a technique to produce tubular composites comprised of beryllium tubes encapsulating and intimately bonded to thin stainless steel or columbium alloy, materials reported to be compatible with the liquid metals used in radiators. The composites were to be used as targets for high-velocity impact experiments simulating meteoroid impact. Target dimensions called for were: tube O.D. of .500 in., tube wall thickness varying from .010 in. to .049 in., armor thickness of .375 in., and lengths from around 2 to 6 inches.

Members of the technical staff of The Beryllium Corporation, Reading, Pennsylvania, performed the work. Melting equipment for direct casting was a bottom-pour vacuum induction furnace. Berylco's 1750-ton Loewy Hydropress was used for extrusion. Brazing (including solid state diffusion bonding) was done with vacuum brazing equipment in the research laboratories.

Fourteen different composite targets, completely or nearly completely sound at the metal interfaces, were produced. These represent a combination of both cast, and cast-extruded beryllium, bonded by direct casting, silver brazing, and solid state bonding, to stainless and columbium alloy tubing of various wall thicknesses.

This report describes the experimental techniques which produced the targets and gives the results of evaluation by metallography and radiography.

EXPERIMENTAL PROCEDURE AND RESULTS

Specimens produced in this investigation (see Table 1) were nominally 1-1/4" O.D. x 6" long. The liners were AISI 316 Stainless Steel and Columbium - 1% Zirconium alloy tubes having a .500" nominal O.D. and nominal wall thicknesses of .010, .020, and .050".

1. Direct Casting of Be-316SS Impact Targets

Conventional vacuum melting furnaces designed for tilt-pour and bottom-pour operations are normally used in casting beryllium ingots (1-4). These furnaces were modified for casting beryllium-stainless steel targets.

Unsuccessful attempts were made with direct casting techniques as follows:

1.1 A casting was produced in a bottom-pour furnace employing a CS-graphite mold with two cavities designed to support a stainless steel tube (0.049 wall, 1/2 in. O.D., 8 in. long) centered in each cavity. Graphite inserts and plugs were machined and installed in the mold to prevent the beryllium metal from filling the tubes and to center the tube in each cavity. A water-cooled chill plug was inserted in the bottom of one cavity; the other contained a graphite plug. A graphite crucible coated with a BeO-$BeSO_4$ slurry was used for melting and was placed on top of the mold assembly. Melting was done under a vacuum of 1000 - 1500 microns and poured through a 3/4 in. diameter tap hole at 2462°F. The heat capacity of the system (graphite mold and water-cooled chill plug) was found to be insufficient to prevent melting of the stainless steel tube as shown in Figure 1. A photograph of the mold assembly and the corresponding casting is shown in Figure 2.

1.2 The possibility of producing cast Be-316SS targets in a tilt-pour furnace was investigated. It was reasoned that the mold in this furnace at an ambient temperature of 120-170°F would, because of its lower temperature, dissipate more heat than the mold in the bottom-pour furnace. In spite of the additional mold heat capacity, however, the stainless steel tubes again melted upon contact with molten beryllium.

A low melting eutectic exists at 2130°F in the system beryllium-iron[5] and the quaternary Be-Fe-Cr-Ni eutectic melts at an even lower temperature. Special cooling devices were accordingly considered, designed to chill the molten beryllium more rapidly than was possible in the experiments previously described. Heat transfer calculations, however, established that the use of a water-cooled plug within the stainless steel would make the operation hazardous. The approach was abandoned in favor of coextrusion, brazing and diffusion bonding as described in Sections 3 and 5.

2. Direct Casting of Be-Cb-1% Zr Impact Targets

A total of nineteen Be-Cb-1% Zr composites were produced by direct casting. Radiographic examination revealed that nine were of satisfactory quality. A graphite mold designed to support a Cb-1% Zr tube in each cavity was cleaned and dried for 24 hours at 300°F. Fiberglas insulation was packed loosely around the mold to eliminate longitudinal cracking of the beryllium from unequal radial heat transfer from each mold cavity. The bottom-pour furnace and melting procedure were those used for casting Be-SS targets; casting parameters and thermal data are given in Tables 2 and 3.

Following the casting operation, the targets were machined and evaluated by radiographic and metallographic techniques. Three x-ray views were obtained at 120° intervals around the target circumference. Voids and cracks, when present, were readily detected and served as the basis for target rejection. The nine surviving targets, evaluated as described, are listed in Table I.

A photograph of a typical target is presented in Figure 3. In a typical microstructure shown in Figure 4, two intermetallic compounds (Be-Cb) approximately 0.001" in total thickness may be observed at the interface. The quality of this bond is considered satisfactory. Photographs of the targets produced from heat 8 are shown in Figures 5 and 6. The chemical analysis of the cast Be-Cb-1% Zr targets are tabulated in Tables 4 and 5.

3. Coextrusion of Beryllium and Stainless Steel

The extrusion of a cast beryllium billet together with a 316SS rod to produce cast-extruded Be-316SS targets met with limited success.

Two billets were extruded at 1950°F and 1800°F. They consisted of cylinders of cast beryllium, 4-1/2 in. O.D., 1-3/4 in. I.D., and 5 in. long, machined to accept stainless steel rods 1-3/4" diameter with a clearance of 0.001". These composites were subsequently clad in mild steel jackets and extruded at a reduction ratio of 12:1 to 1.589" diameter.

The extrusions were evaluated by sectioning into 6" lengths and examining the cross sections. Segments from the nose, center and tail of each extrusion were polished, etched and examined macroscopically. Extensive study revealed that no rod sections were of satisfactory quality.

The sections of coextruded rod are illustrated in Figures 7 and 8 The 1950°F extrusion temperature yielded a smoother surface than that at 1800°F. The stainless steel rods were severely deformed in both cases, but no satisfactory bond between beryllium and stainless steel was achieved. Examination of macroscopic cross sections (Figures 9 and 10) also reveals periodic cracking of the beryllium. This is attributed to mechanical interlocking at the interface with excessive stresses induced by the different coefficients of expansion of beryllium and stainless steel.

4. Silver Brazing of Be-SS Impact Targets

In view of the difficulties experienced in producing beryllium-stainless steel impact targets by direct casting or coextrusion, the possibility of silver brazing was considered applicable to both cast and cast-extruded beryllium.

Four cast and four cast-extruded cylinders were silver brazed to stainless steel tubes with wall thicknesses of 0.010", 0.028", and 0.049". The procedure for silver brazing beryllium to stainless steel tubes is as follows:

4.1 The beryllium cylinders were machined on the I.D. to within 0.001" of the O.D. of each of the stainless steel tubes.

4.2 The stainless steel tubes were plated with 0.0005" of silver and heated at 1775°F for 15 minutes in an argon atmosphere.

4.3 After cooling, the pieces were cleaned to remove non-adhering coating and replated to give a uniform coating 0.0005" thick.

4.4 The beryllium cylinders were etched and then plated with silver 0.0005" on the inside with provisions for assembly tolerance of 0.001".

4.5 The stainless steel tubes were assembled in the beryllium cylinders, encased in a welded retort. Leak rate of the retort was less than 20 microns per hour.

4.6 The retort was purged and evacuated three times with helium at room temperature and again at 400°F.

4.7 The retort was held at 400°F for 45-1/2 hours until the outgassing rate had dropped from 1600 microns per hour to 16 microns per hour.

4.8 The retort was then heated to 1000°F and held for 15 minutes before bringing it to the brazing temperature of 1625°F, which was maintained for 10 minutes under an argon flow of 10 CFH.

4.9 The retort was cooled at the same argon flow rate to 1500°F, then to room temperature in a static argon atmosphere. The retort was examined and found to be exceptionally clean, an indication of a satisfactory brazing atmosphere.

The choice of a 1625°F/10 min. brazing cycle is based on the silver-1% beryllium eutectic melting temperature of 1616°F, and the advisability of limiting the diffusion of beryllium into the stainless steel with concurrent formation of brittle intermetallics.

Radiographs were made of the brazed targets at 120° intervals around the circumference of the targets. All targets appeared to be free of internal defects except one cast Be-.028" wall SS target. Each target was further evaluated by cutting wafers from the ends and observing the structure at several magnifications. Illustrations can be seen in Figures 11 through 15. Seven (7) of the eight (8) composites exhibit inconsistent braze quality. The eighth, mentioned above, was found to contain extensive interfacial defects. Measurements indicate that about 50 per cent bonding occurred with the as-cast beryllium, but about 70 per cent in the targets containing cast-extruded metal. Incompletely bonded areas can be seen as a dark line in the microscopic views of Figures 13 and 14. The chemical analyses of these impact targets are presented in Tables 6 and 7.

Incomplete bonding is attributable to the tendency of silver (thermal exp. coefficient = 10.9 in./in./°F) and type 316SS (thermal exp. coefficient = 9.2 in./in./°F) to shrink away from the beryllium (thermal exp. coefficient = 6.9 in./in./°F), during the cooling portion of the brazing cycle. Differences in thermal expansion of the materials induce stresses and cracking may occur, particularly in brittle int metallic phases. Defective areas appear as dark lines in Figures 13 and 14. Microhardness measurements were made at five points across the brazed interface of a cast Be-.028" wall SS target, to confirm the existence of intermetallic compounds as illustrated in Figure 16, with the following results.

Location	Knoop Hardness Number (25 gram load)
Beryllium	214
Silver	83
First Intermetallic	1,220
Second Intermetallic	592
Stainless Steel	225

Three cast beryllium-stainless steel impact targets were of satisfactory quality: each 3-1/4" long with stainless steel wall thicknesses of .010", .028" and .049". Four cast and extruded beryllium-stainless steel impact targets were also of satisfactory quality: one 6" long containing .028" wall stainless steel tubing, and three 3-1/4" long with stainless steel wall thicknesses of .010", .028" and .049". Five of these targets were shipped to NASA for evaluation. Two cast and extruded beryllium targets were selected to investigate bonding by solid state diffusion as next described.

5. Diffusion Bonding of Cast and Extruded Be-SS Impact Targets

Three stainless steel tubes were silver plated with a .0005" deposit on the radius, and fired at 1775°F for 15 minutes. After cooling, they were wire brushed, inspected for adherence of the coating, and found to be free of blisters. Mating beryllium tubes were etched, silver-plated and reamed. Approximately .0005" of plating remained on the radius, with fit-up conditions held to close tolerances. The assemblies were then exposed at 1450°F for 2 hours in vacuum (.07 microns), in order to effect a diffusion bond.

A control hot pressed assembly, processed simultaneously, was sectioned and examined metallographically. Partial diffusion bonding was found to have occurred, with a fine partition line periodically observed at 300 magnifications. The three targets (Figure 17) were delivered to NASA. Silver brazed and diffusion bonded beryllium-stainless steel composites delivered to NASA are summarized in Table I.

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CONCLUDING REMARKS

Construction of hypervelocity impact targets by direct casting of beryllium around 1/2" O.D. Columbium-1% Zirconium tubes was successfully demonstrated. Attempts to cast beryllium around 1/2" O.D. AISI 316 tubes were not successful because of the formation of the low melting point Fe-Cr-Ni-Be eutectic at the interface and the limited capacity for cooling the mold cavity. The means investigated for producing a cast beryllium-316 stainless steel composite were coextrusion, silver brazing, and silver diffusion bonding. A degree of success was achieved with the last two methods. However, coextrusion of the two materials was not successfully demonstrated.

Future efforts to develop reliable joint systems involving beryllium should be directed toward a prior study of the applicable process followed by an applications study involving joint design.

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TABLE I

BERYLLIUM TARGET DESIGNATION

Item	Beryllium Description & Bonding Process	Liner Material & Wall Thickness	Quantity and Length	Be Heat No.
1	Cast in Place	Cb-1% Zr .010" Wa.	1 Pc. 3-1/4" Lg.	6
			2 Pcs. 6" Lg.	8
			1 Pc. 6" Lg.	9
2	Cast in Place	Cb-1% Zr .028" Wa.	1 Pc. 6" Lg.	9
			1 Pc. 3-1/4" Lg.	9
3	Cast in Place	Cb-1% Zr .049" Wa.	1 Pc. 6" Lg.	3
			1 Pc. 3-1/4" Lg.	6
			1 Pc. 6" Lg.	8
4	Cast - Silver Brazed	316SS .010" Wa.	1 Pc. 3-1/4" Lg.	AF-13
5	Cast - Silver Brazed	316SS .028" Wa.	1 Pc. 3-1/4" Lg.	AF-13
6	Cast and Extruded - Silver Brazed	316SS .028" Wa.	1 Pc. 3-1/4" Lg.	XP-314
7	Cast - Silver Brazed	316SS .049" Wa.	1 Pc. 3-1/4" Lg.	AF-13
8	Cast and Extruded - Silver Brazed	316SS .049" Wa.	1 Pc. 3-1/4" Lg.	XP-315
9	Cast and Extruded - Diffusion Bonded	316SS .049" Wa.	1 Pc. 3-1/4" Lg.	XP-314
			2 Pcs. 2-15/16" Lg.	XP-315

TABLE 2

CASTING PARAMETERS OF Be-Cb-1% Zr Targets

Heat No.	Mold Design	Charge Wt. of Beryllium Metal lb.	Tap Hole Dia. In.	No. and Wall Thickness of Cb-1% Zr Tubes (1/2 in. O.D. by 8 in. long) in.
3	2 Cavity Mold, Graphite Chill Plug	3.59	3/4	1-0.028 1-0.049
4*	4 Cavity Mold, Water Cooled Chill Plug	6.09	3/4	2-0.010 1-0.028 1-0.049
5	4 Cavity Mold, Water Cooled Chill Plug	6.04	3/4	2-0.010 1-0.028 1-0.049
6	4 Cavity Mold, Water Cooled Chill Plug	7.0	3/4	1-0.010 2-0.028 1-0.049
7	2 Cavity Mold, Water Cooled Chill Plug	4.0	3/4	Blanks 4-Test Bars 3/8"O.D. by 6" long
8	4 Cavity Mold, Graphite Chill Plug	7.0	3/4	2-0.010 2-0.049
9	4 Cavity Mold, Graphite Chill Plug	7.0	3/4	1-0.010 2-0.028 1-0.049

Note: *Tap rod broke during tapping operation

TABLE 3

THERMAL DATA OF CAST Be-Cb-1% Zr TARGETS

Heat No.	Tapping Temp. °F	Mold Temp. At Tapping		Mold Temp. 4 min. after Tapping		Mold Temp. 50 min. after Tapping		Average Cooling Rate (4-50 min. interval)	
		Top °F	Bottom °F	Top °F	Bottom °F	Top °F	Bottom °F	Top °F/Min	Bottom °F/Min
3	2489	1373	869	1904	1256	1112	1040	17.2	4.7
4*	2489	----	---	----	----	----	----	----	---
5	2480	1679	1103	2057	1418	1274	1103	17.0	6.8
6	2498	1652	968	2030	1364	1220	1112	17.6	5.5
7	2489	1562	851	2075	1292	1076	1004	21.7	6.3
8**	2480	----	---	----	----	----	----	----	---
9	2480	1544	1058	1967	1526	1346	1328	13.5	4.3

Note: * Tap rod broke during tapping operation
** Thermocouple failure

TABLE 4

*CHEMICAL ANALYSES OF CAST BERYLLIUM --
Be-Cb-1% Zr Targets

IMPURITY CONTENT	HEAT NO. 3	HEAT NO. 6	HEAT NO. 7	HEAT NO. 8	HEAT NO. 9
BeO	0.17%	0.19%	0.32%	0.39%	0.22%
C	0.173%	0.038%	0.056%	0.081%	0.071%
Fe	580	570	570	570	530
Al	650	440	410	390	460
Mg	35	40	35	50	40
Ni	120	110	90	140	100
Mn	95	120	100	125	115
Cr	50	55	55	55	50
Ca	<200	<200	<200	<200	<200
Co	<5	<5	<5	<5	<5
Cu	50	65	50	55	65
Zn	<100	<100	<100	<100	<100
Ag	5	5	5	10	5
Pb	<3	<3	<3	<3	<3
Si	380	380	350	370	340
Mo	<10	<10	<10	<10	<10
Ti	260	230	160	180	200

Note: * Concentration in PPM unless otherwise noted

TABLE 5

*CHEMICAL ANALYSES OF Cb-1% Zr TUBES

Impurity Content	Wall Thickness 0.010	Wall Thickness 0.028 and 0.049
O	130	210
C	76	70
N	52	40
H	3.4	3.0
B	<1	<1
Fe	<100	113
Al		<20
Mg		<20
Ni	20	<20
Mn	20	<20
Cr		<20
Co		<10
Cu		<40
Sn		<10
Pb	<20	<20
Si	100	<50
Mo	70	<20
Ti	<150	<40
Ta	780	<500
Hf	<80	<80
Cd	<5	<5
W	<300	190
V	<20	<20
Total R. E.	<100	<100
Zr	0.94%	1.18%
Cb	Balance	Balance

Note: *Concentration in PPM unless otherwise noted

TABLE 6

*CHEMICAL ANALYSES OF BERYLLIUM METAL
IN Be-SS IMPACT TARGETS

Impurity Content	Cast Beryllium AF-13	Cast-Extruded XP-314	Beryllium XP-315
BeO	0.15%	0.17%	0.25%
C	0.069%	0.035%	0.043%
Fe	550	2750	350
Al	350	1100	290
Mg	40	<30	30
Ni	100	510	75
Mn	80	145	85
Cr	40	210	30
Ca	<200		
Co	<5		
Cu	50	<1000	75
Zn	<100		
Ag	5		
Pb	<3		
Si	<250	850	315
Mo	<10		
Ti	160	150	480

Note: *Concentration in PPM unless otherwise noted

TABLE 7

CHEMICAL ANALYSES OF STAINLESS STEEL TUBES

Impurity Content	316 SS Tubing 0.010 Wall	316 SS Tubing 0.028 Wall and 0.049 Wall
Comb. C	0.061%	0.040%
Mn	1.45 %	1.84 %
Si	0.397%	0.564%
Ni	12.77 %	13.65 %
Cr	18.58 %	17.13 %
Mo	2.66 %	2.31 %

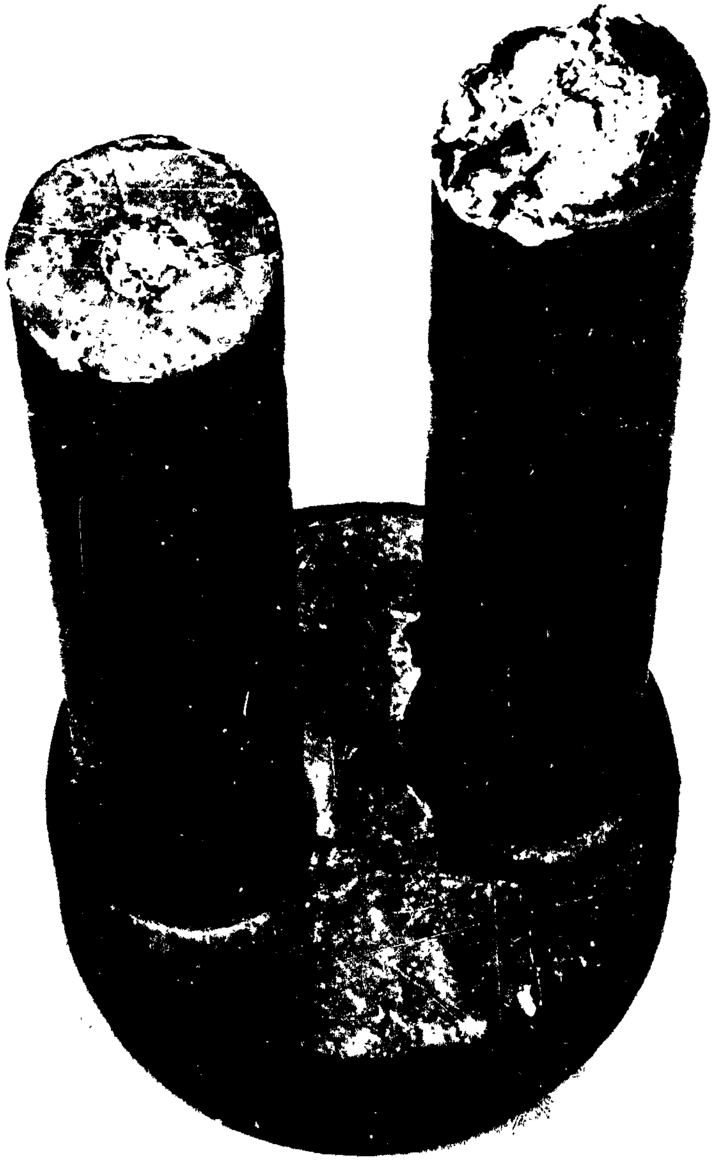


FIGURE 1. CAST BERYLLIUM AROUND STAINLESS STEEL TUBES, HEAT NO. 1

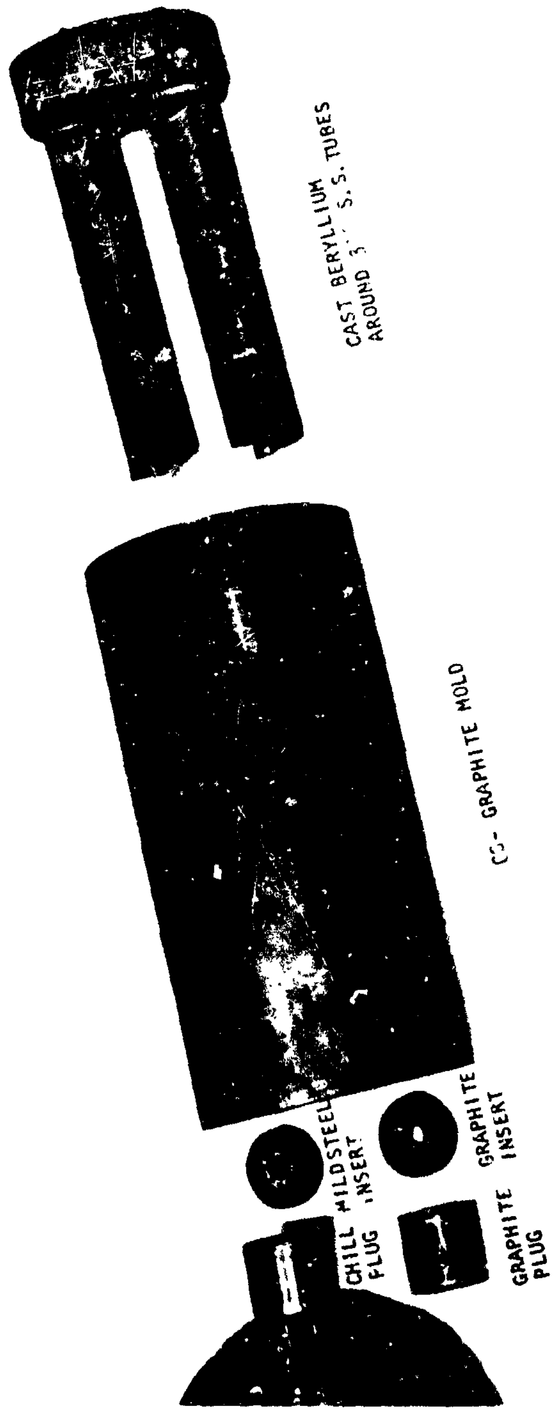


FIGURE 2. MOLD ASSEMBLY FOR CASTING BERYLLIUM METAL AROUND STAINLESS STEEL TUBES

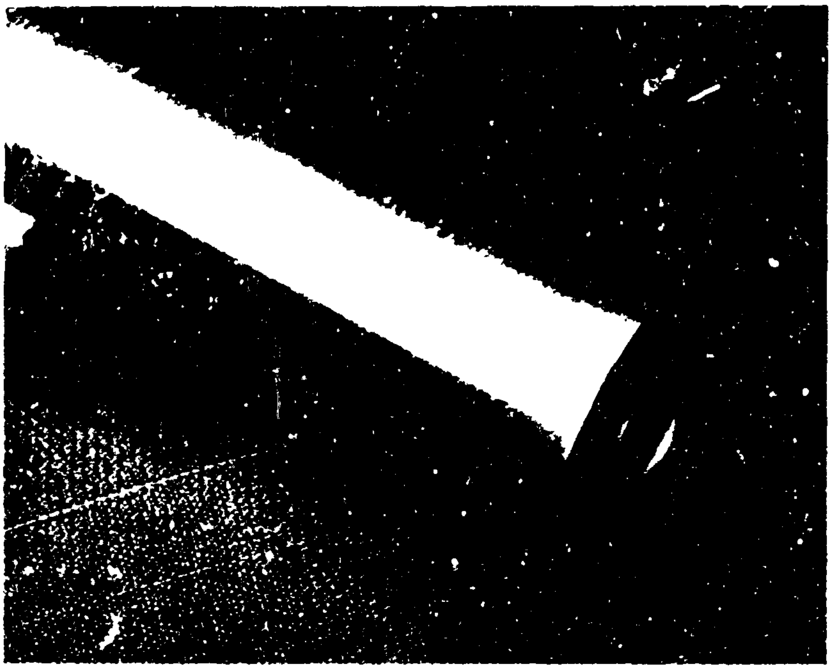


FIGURE 3. CAST BERYLLIUM AROUND 0.049 WALL Cb-1% Zr TUBE, HEAT NO. 3, PC. #2, 1-1/4 IN. O.D. BY 6 IN. LENGTH

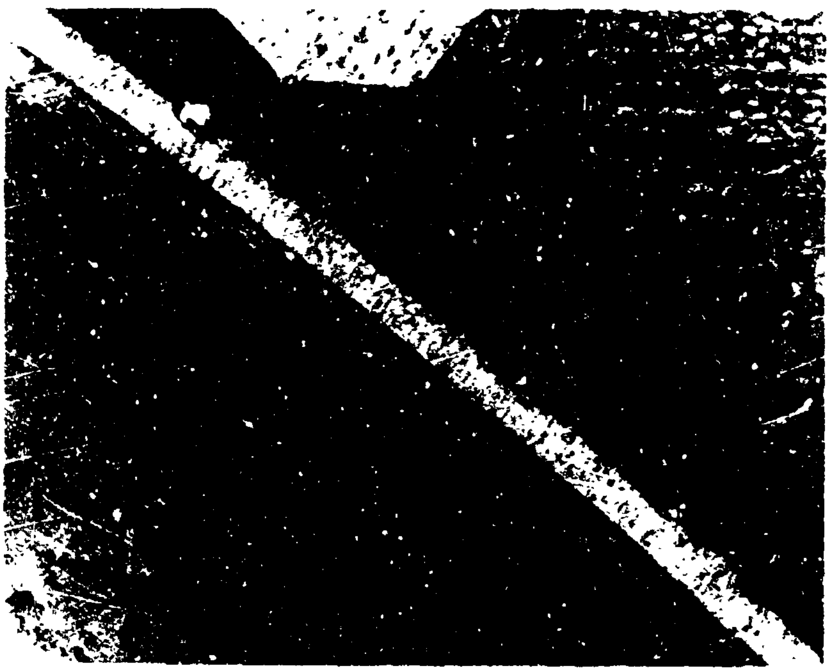
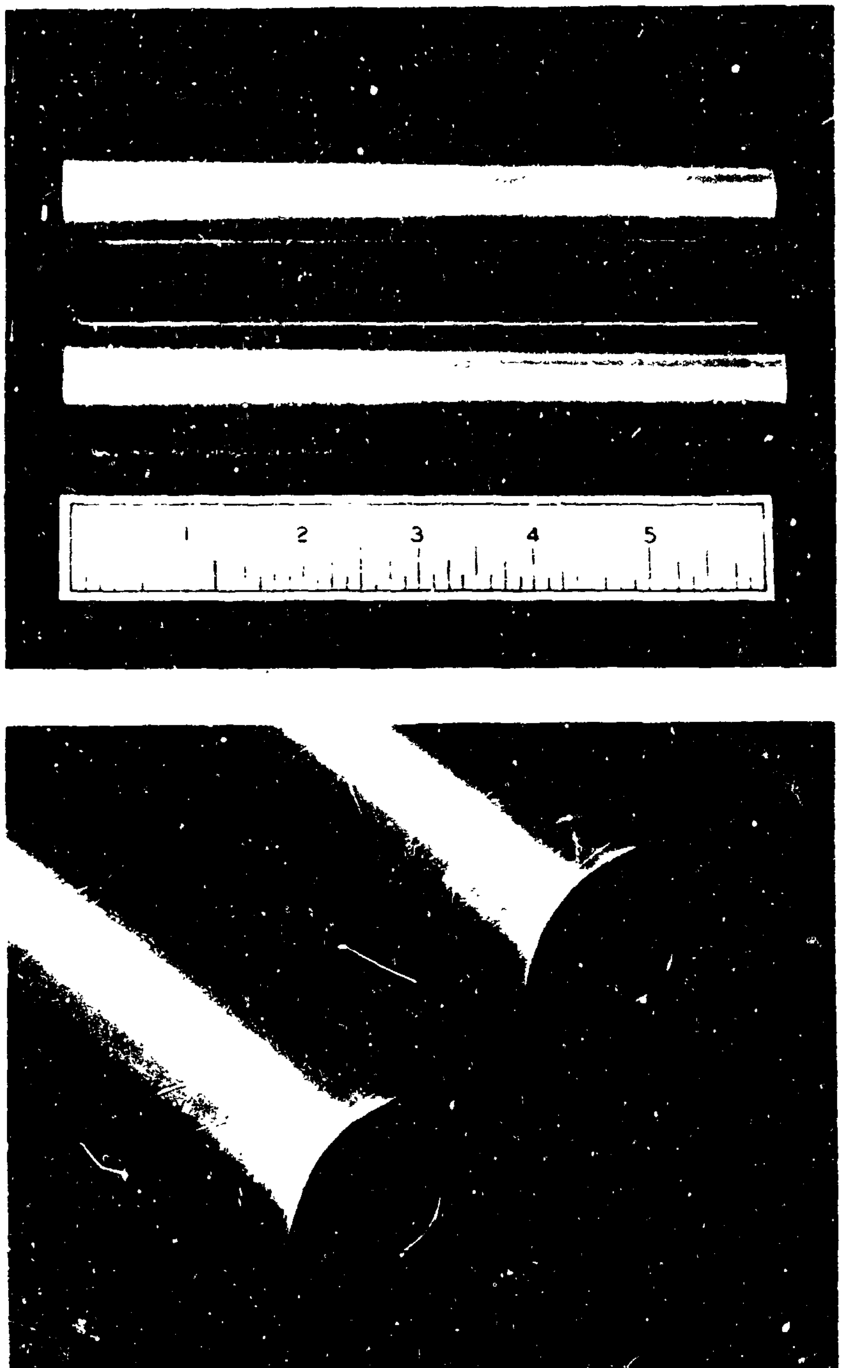


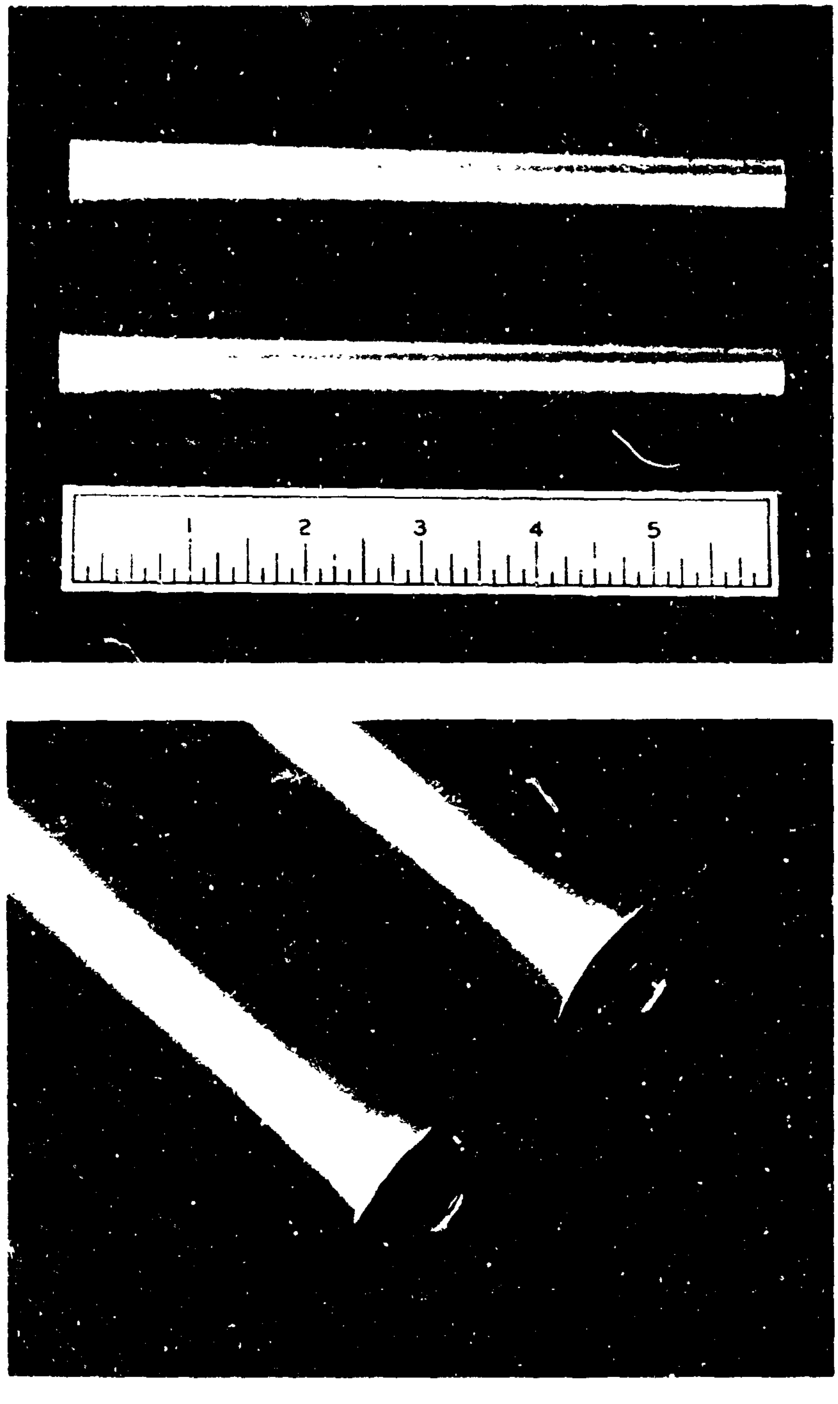
FIGURE 4. THE INTERFACE OF HEAT NO. 3, PC. NO. 2 (POLARIZED LIGHT 150X)



SIDE VIEW

END VIEW

FIGURE 5. CAST BERYLLIUM AROUND 0.010 WALL CB-1% Zr TUBES, HEAT NO. 8, PC. #1 AND PC. #2



SIDE VIEW

END VIEW

FIGURE 6. CAST BERYLLIUM AROUND 0.049 WALL Cb-1% Zr TUBES, HEAT NO. 8, PC. #3 AND PC. #4

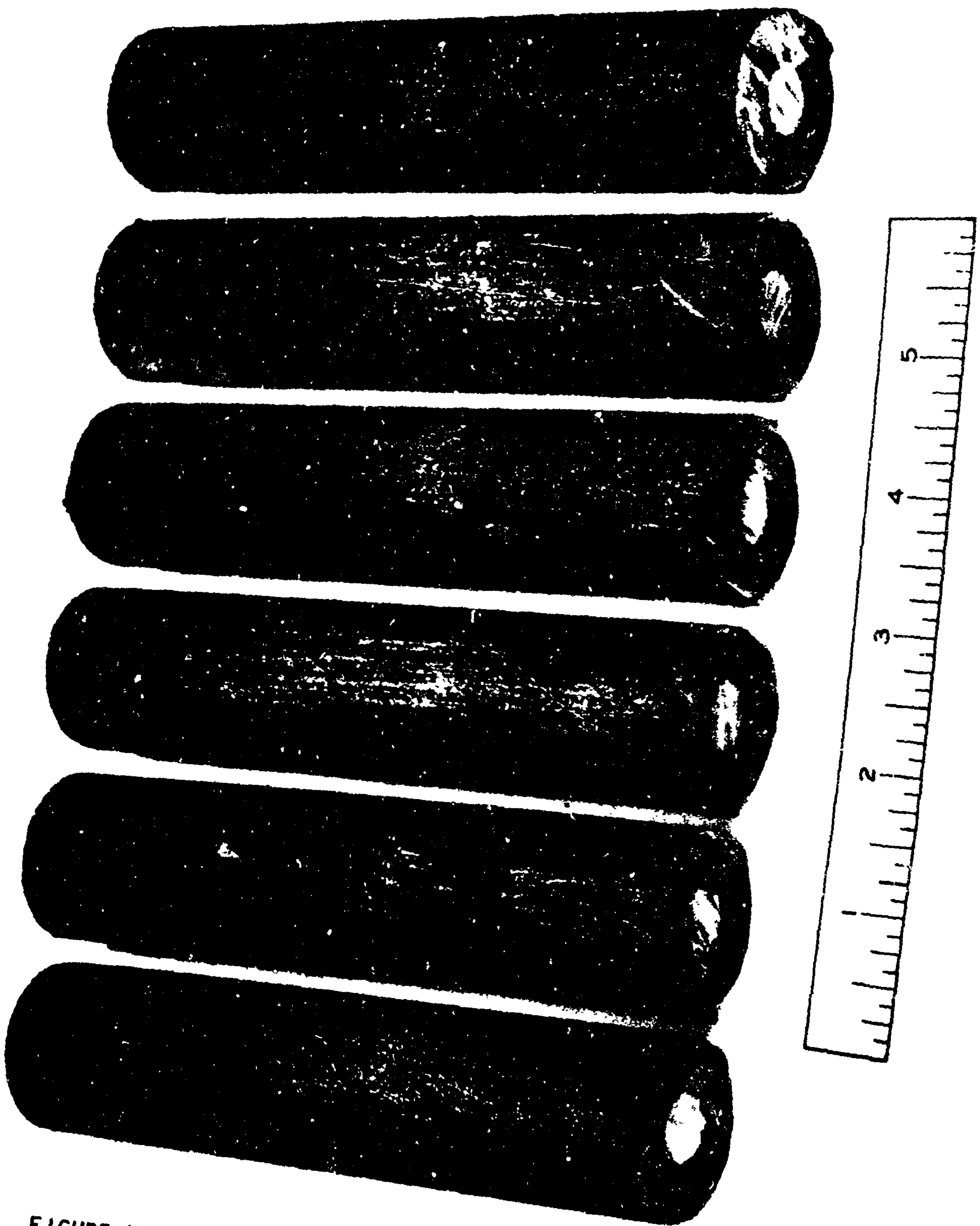


FIGURE 7. BERYLLIUM-STAINLESS STEEL COEXTRUSION AT 1950°F

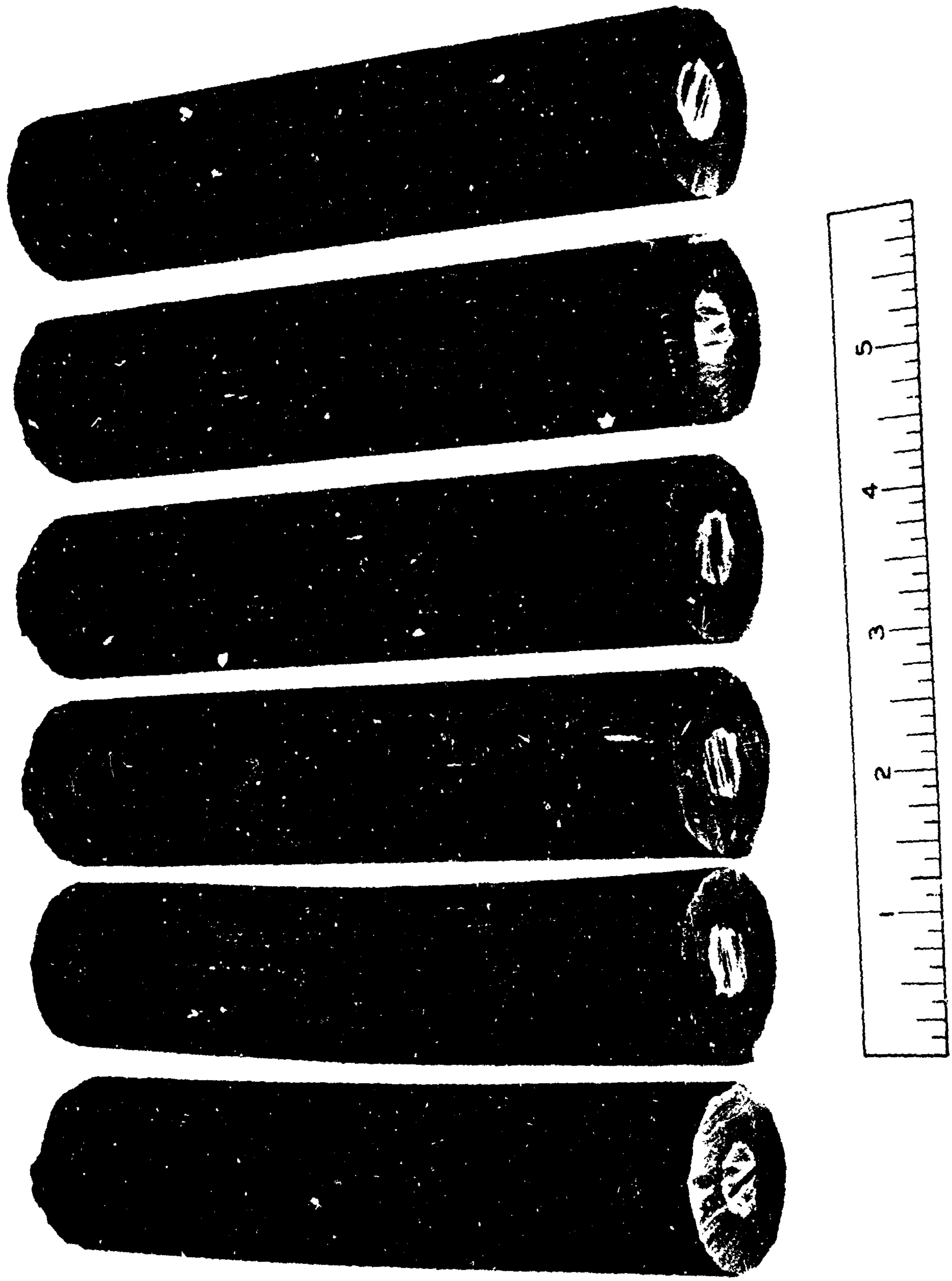


FIGURE 8. BERYLLIUM-STAINLESS STEEL COEXTRUSION AT 1800°F

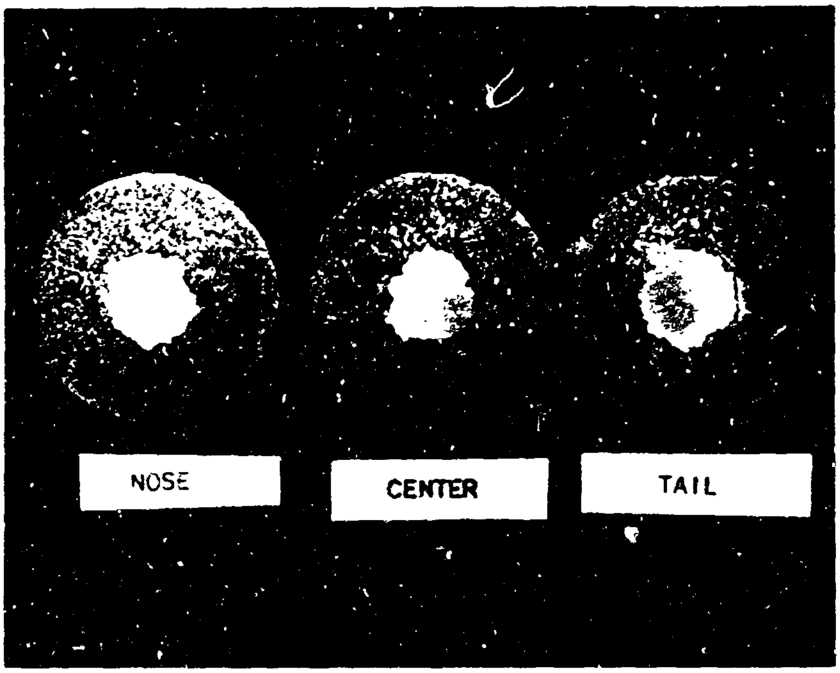


FIGURE 9. MACROSCOPIC CROSS-SECTION OF BERYLLIUM-STAINLESS STEEL COEXTRUSION AT 1950°F (POLARIZED LIGHT 1X)

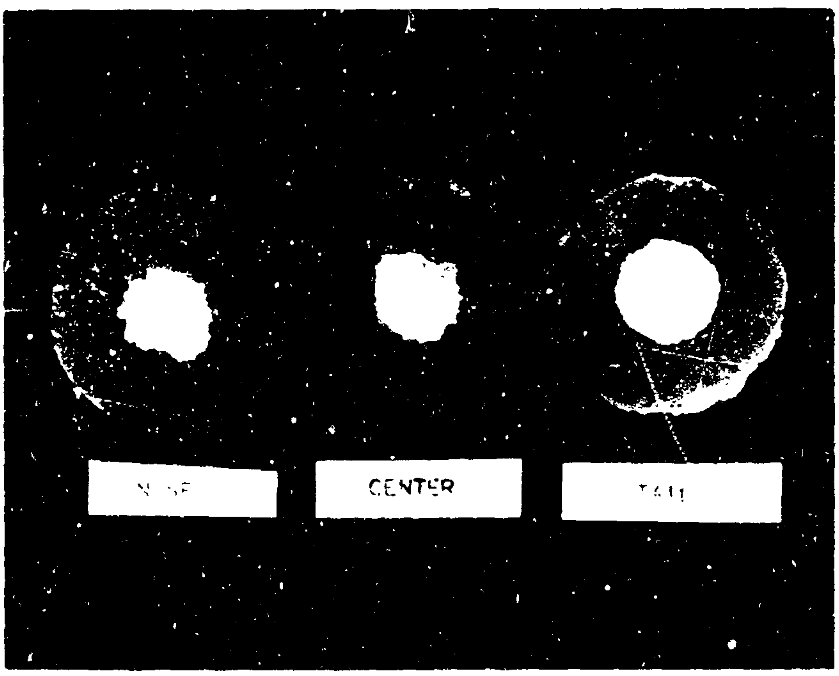
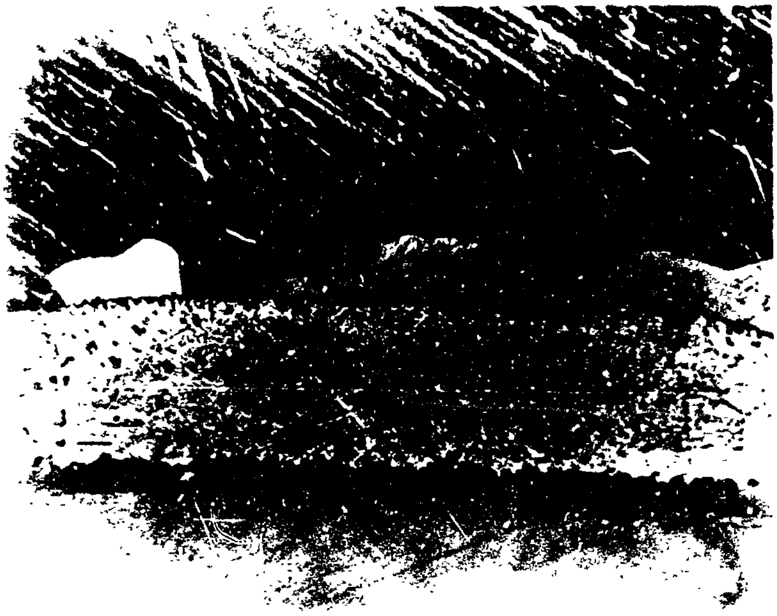


FIGURE 10. MACROSCOPIC CROSS-SECTIONS OF BERYLLIUM-STAINLESS STEEL COEXTRUSION AT 1800°F (POLARIZED LIGHT 1X)



150X

1.5X

FIGURE 11. CAST BERYLLIUM-STAINLESS STEEL IMPACT TARGET; SILVER BRAZED (SS TUBE, .010" WALL)

150X

1.5X

FIGURE 12. CAST BERYLLIUM-STAINLESS STEEL IMPACT TARGET; SIL\VER BRAZED (SS TUBE, .028" WALL)

CAST BERYLLIUM

SILVER BRAZE

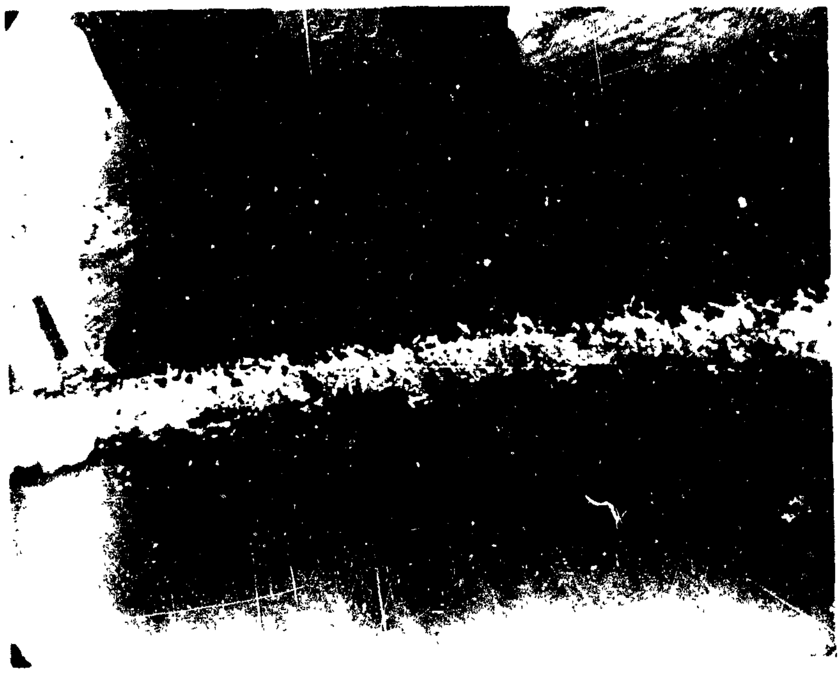
--CRACK

316 STAINLESS
STEEL

150X

1.5X

FIGURE 13. CAST BERYLLIUM-STAINLESS STEEL IMPACT TARGET;
SILVER BRAZED (SS TUBE, .049" WALL)

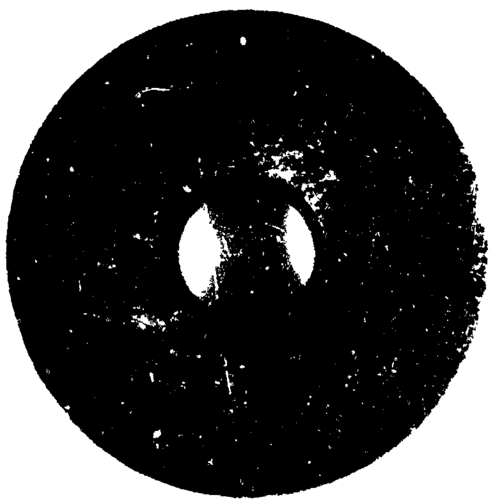


CAST-EXTRUDED
BERYLLIUM

SILVER BRAZE

316 STAINLESS
STEEL

150X



1.5X

FIGURE 14. CAST AND EXTRUDED BERYLLIUM-STAINLESS STEEL IMPACT TARGET; SILVER BRAZED (SS TUBE, .028"WALL)

150X

1.5X

FIGURE 15. CAST AND EXTRUDED BERYLLIUM-STAINLESS STEEL IMPACT TARGET; SILVER BRAZED (SS TUBE, .049" WALL)

200X

FIGURE 16. HARDNESS INDENTATION ACROSS BRAZED INTERFACE
(CAST BERYLLIUM - .028" WALL SS TUBE)

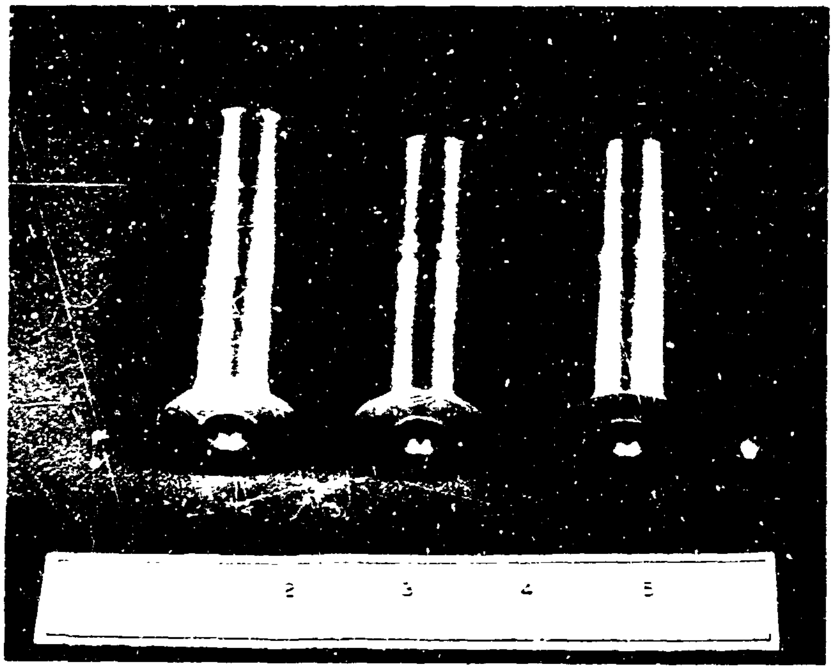


FIGURE 17. CAST AND EXTRUDED BERYLLIUM--STAINLESS STEEL TARGETS; DIFFUSION BONDING

NASA CONTRACTOR REPORT

CASTING OF BERYLLIUM-STAINLESS STEEL

AND

BERYLLIUM-COLUMBIUM IMPACT TARGET COMPOSITES

The Beryllium Corporation

ABSTRACT

Methods have been developed for the production of hypervelocity impact target composites, consisting of cast beryllium surrounding stainless steel tubing and cast beryllium surrounding columbium--1% zirconium tubing. Seventeen targets were successfully produced preparatory to subsequent impact testing. Experimental methods used to produce the targets are described.